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Agro-meteorological indices and their relationship with yield of finger millet (*Eleusine coracana* L.) under different sowing windows in semi-arid Maharashtra

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Abstract
A field experiment was conducted during Kharif 2024 at the Agricultural Meteorology Research Farm, College of Agriculture, Pune, Maharashtra, India, to evaluate the impact of sowing windows and varietal differences on agro-meteorological indices and their relationship with finger millet yield. The experiment followed a split-plot design with four sowing windows (24, 26, 28, and 30 Meteorological Weeks) and three varieties (Phule Nachani, Phule Kasari, and Dapoli-3). Observations were recorded for Growing Degree Days (GDD), Photo-Thermal Units (PTU), Helio-Thermal Units (HTU), Hydro-Thermal Units (HyTU), Heat Use Efficiency (HUE), Light Use Efficiency (LUE), and weather-yield relationships. Results indicated that sowing during 26 MW with the variety Phule Kasari accumulated the highest thermal and hydrothermal units, achieved superior efficiency indices, and produced maximum yield. Grain yield showed significant positive correlations with rainfall ($r = 0.72$*) and relative humidity ($r = 0.65$*), and a negative correlation with maximum temperature ($r = -0.68$*). The study highlights the predictive value of agro-meteorological indices in optimizing sowing schedules and ensuring climate-resilient millet production in semi-arid regions.

Keywords: Finger millet, growing degree days, heat use efficiency, sowing windows, climate resilience

Introduction
Finger millet (*Eleusine coracana* L.) is a climate-resilient and nutritionally rich minor millet cultivated extensively in the semi-arid tropics. Commonly known as ragi, it is an important small millet crop grown widely in the semi-arid regions of Maharashtra and other parts of India. The crop is highly valued for its superior nutritional profile, which includes high levels of calcium, dietary fiber, protein, and essential micronutrients, making it a vital contributor to regional food and nutritional security (Vinay T. *et al*., 2020; Rajkumar *et al*., 2024) [19, 15]. It serves as a staple food for low-income populations in India (Devi *et al*., 2011) [7]. Its inherent drought tolerance and adaptability to marginal soils allow successful cultivation under rainfed conditions, thereby supporting the livelihoods of smallholder farmers in semi-arid environments characterized by erratic rainfall and high temperature variability (Sawargaonkar *et al*., 2025) [17]. However, despite its resilience, finger millet yields remain suboptimal, primarily due to climatic variability, inappropriate sowing windows, and unsuitable varietal choices. Climate change further exacerbates these challenges by intensifying temperature extremes, increasing rainfall irregularities, and altering solar radiation patterns.

Agro-meteorological indices, such as Growing Degree Days (GDD), Helio-Thermal Units (HTU), Photo-Thermal Units (PTU), Hydro-Thermal Units, Light Use Efficiency (LUE), and Heat Use Efficiency (HUE), provide a quantitative framework to understand the cumulative effects of temperature, solar radiation, and moisture on crop phenology and yield formation (Singh *et al*., 2017) [18].These indices are critical for understanding phenological development, optimizing sowing windows, and ensuring efficient utilization of environmental resources. The present study was designed to quantify the influence of sowing windows and varietal choice on agro-meteorological indices, efficiency parameters, and yield performance of finger millet under semi-arid conditions of Maharashtra.

Materials and Methods

Experimental Site

The study was conducted at the Agricultural Meteorology Research Farm, College of Agriculture, Pune (18°32′N, 73°51′E, 559 m MSL) during Kharif 2024. The soil type was medium-fertile Vertisol with good water-holding capacity.

Experimental Design

The experiment followed a split-plot design with four sowing windows (24 MW, 26 MW, 28 MW, and 30 MW) as main plots and three finger millet varieties (Phule Nachani, Phule Kasari, Dapoli-3) as sub-plots, replicated thrice. Standard agronomic practices were followed.

Weather Data

Daily maximum and minimum temperature, relative humidity, sunshine hours, rainfall, and day length were recorded from the on-site observatory.

Indices Calculated

- **GDD:** Σ [(Tmax + Tmin)/2 - Tb], with base temperature =10°C.
- **HTU:** GDD × Sunshine hours.
- **HyTU:** GDD × Relative humidity.
- **PTU:** GDD × Day length.
- **HUE:** Grain or biomass yield ÷ accumulated GDD (kg ha^{-1} °C day^{-1}).
- **LUE:** Grain yield ÷ absorbed PAR (MJ m^{-2}).

Agro-meteorological indices

The following indices were calculated to evaluate the influence of weather on crop growth:

Growing Degree Days (GDD)

Growing Degree Days (GDD) is defined as “the cumulative sum, over the growing season of a crop, of the difference between the daily mean temperature and a reference temperature.” GDD is expressed in °C day. It was calculated using a base temperature of 10 °C (Kamboj E. *et al*., 2022; Chavan KK *et al*., 2018) [11, 4]. The total GDD for different phenophases was determined using the following equation.

$$\text{Accumulated GDD (°C day)} = \Sigma^{n} [(T_{max} + T_{min}) / 2] - T_b$$

Where,
GDD = Growing degree days
Tmax = Daily maximum temperature (°C)
Tmin = Daily minimum temperature (°C)
Tb = Base temperature (10 °C)

Light Use Efficiency (LUE)

Light Use Efficiency (LUE) is a measure of the efficiency with which plants convert absorbed solar radiation into biomass (biological yield). It plays a key role in assessing crop productivity under varying light conditions. LUE was calculated using the following expression (Balagond S. *et al*. 2020) [2].

$$\text{LUE} = \frac{\text{Amount of green/ dry matter produced (g/m2)}}{\text{Amount of cumulative light absorbed PAR (MJ/m2)}}$$

Helio-thermal Units (HTU)

Helio-Thermal Units (HTU) are defined as the accumulated product of Growing Degree Days (GDD) and bright sunshine hours between the developmental thresholds for each day. HTU is expressed in °C day hours. It is calculated as the product of GDD and the mean daily bright sunshine hours. The cumulative HTU for each phenophase was determined using the following equation (Nandini, K. M. and Sridhara, S., 2019) [13].

$$\text{Accumulated HTU (°C day hrs)} = \text{GDD} \times \text{BSS}$$

where,
HTU = Helio-Thermal Units
GDD = Growing Degree Days
BSS = bright sun shine hours

Hydrothermal unit (HyTU)

Hydrothermal Units (HyTU) for various growth stages were calculated using the following formula (Md. Tauhid Hossain *et al*. 2024) [12].

$$\text{HyTU} = \text{GDD} \times \text{Average relative humidity}$$

Photothermal unit

Photothermal Units (PTU) are used to quantify the combined effect of temperature and day length on plant growth ((Pandey *et al*. 2010) [14]. PTU for various growth stages were calculated using the following formula.

$$\text{PTU} = \text{GDD} \times \text{DL}$$

Where,
DL = Day length

Heat use efficiency

Heat Use Efficiency (HUE) refers to the efficiency with which plants convert accumulated thermal energy, expressed in terms of Growing Degree Days (GDD), into biological yield. It is a useful parameter for assessing the effectiveness of crops in utilizing available heat for growth. HUE was calculated using the following expression (Nagaraju D. *et al*., 2022) [5]

$$\text{HUE} = \text{biological yield (kg/ha)/ accumulated GDD}$$

Results and Discussion

The performance of finger millet varieties under different sowing windows was assessed using a suite of agro-meteorological indices: Growing Degree Days (GDD), Helio-Thermal Units (HTU), Photothermal Units (PTU), Hydrothermal Units (HyTU), Heat Use Efficiency (HUE), and Light Use Efficiency (LUE). These indices capture the interactions between temperature, light, and moisture, providing an integrated view of crop-climate relationships. The following section presents the results in detail, supported with physiological interpretations, literature comparisons, and implications for climate-resilient crop management.

Growing Degree Days (GDD)

The cumulative GDD requirement of finger millet from sowing to maturity showed clear differences among varieties and sowing windows (Table 1; Figure 1). Across varieties, the highest requirement was observed in Dapoli-3 (V_3) with 1932.8 °C days, followed by Phule Nachani (V_1) with 1879.4 °C days, while Phule Kasari (V_2) required the least (1631.8 °C days). This reflects the variation in crop duration, with Dapoli-3 being late-maturing and Phule Kasari early-maturing. Similar varietal variability in thermal time requirements of finger millet has been reported by Kulkarni *et al*. (2022) [21] and Ray *et al*. (2024b) [22], who observed significant differences in accumulated heat units among genotypes differing in maturity duration.

Among sowing windows, crops established in the 24th Meteorological Week (MW) accumulated the maximum GDD (1832.1 °C days), while sowing in the 30th MW resulted in the lowest (1799.0 °C days). Intermediate values were recorded in 26th MW (1816.4) and 28th MW (1811.2). These differences indicate that early sowing prolongs the crop cycle and enhances thermal accumulation, while late sowing shortens the effective duration due to higher late-season temperatures that hasten phenological progression. Similar effects of delayed sowing on thermal accumulation were also noted in millets by Nandini and Sridhara (2019) [13], who reported reduced GDD and grain filling duration under late sowing conditions.

Stage-wise distribution revealed that the vegetative-to-flowering (P_3) and grain filling-to-maturity (P_6) stages accounted for the highest thermal demands. For instance, Dapoli-3 required 756.3 °C days during P_3 alone. Phule Kasari, on the other hand, achieved maturity with significantly fewer degree days, underlining its suitability for environments with shorter growing seasons or terminal heat stress. These patterns highlight the critical role of genotype × sowing time interactions in optimizing GDD utilization.

Similarly, the Photothermal Units (PTU) recorded in the study illustrated a close relationship between GDD and day length, where the above-mentioned cultivars registered superior performance. Comparable findings were reported by Ray *et al*. (2024b) [22] and Kulkarni *et al*. (2022) [21] in finger millet and by Nandini and Sridhara (2019) [13] in foxtail millet, confirming that both thermal and photothermal accumulation play decisive roles in determining growth duration and yield potential of small millets.

Helio-Thermal Units (HTU)

HTU values, combining GDD and sunshine hours, also exhibited significant variation (Table 2; Figure 2). Among varieties, Dapoli-3 accumulated the highest HTU (8771.3 °C day hours), followed by Phule Nachani (8426.8), while Phule Kasari had the lowest (6653.7). The longer duration of Dapoli-3, and consequently longer exposure to solar radiation, contributed to its higher HTU accumulation reported that late-maturing finger millet genotypes tend to accumulate more HTU due to extended radiation interception.

Interestingly, sowing windows displayed the opposite trend compared to GDD. The 30th MW (S4) accumulated the highest HTU (9658.3 °C day hours), while the 24th MW (S1) had the lowest (6769.1). This can be explained by the fact that late-sown crops are exposed to higher radiation intensity and higher diurnal temperatures, even though their growth duration is shorter, effects in sorghum, noting that later sowings experience increased heliothermal load, though not always with positive yield outcomes.

The reproductive phases (P5 and P6) demanded the greatest HTU across all treatments, confirming that grain filling is the most energy-intensive period. Dapoli-3, for example, required 5558.6 °C day hours during grain filling to maturity. These results suggest that while higher HTU reflects greater energy availability, its positive impact depends on synchrony with sensitive growth stages. Delayed sowing (S4) may accumulate more HTU, but often coincides with terminal stress that limits grain filling efficiency.

Photothermal Units (PTU)

PTU, which integrate GDD with photoperiod, showed distinct varietal and sowing-time effects (Table 3; Figure 3). Dapoli-3 again recorded the maximum PTU (23,338.9 °C day hours), followed by Phule Nachani (22,855.8), while Phule Kasari had the lowest (20,078.5). The higher PTU requirement of Dapoli-3 highlights its photoperiod sensitivity and longer growth cycle. Phule Kasari, in contrast, demonstrated relative photoperiod insensitivity, enabling it to complete its life cycle under reduced PTU conditions

Sowing time strongly influenced PTU accumulation. The 24th MW (S1) registered the maximum PTU (22,872.6), while the 30th MW (S4) recorded the lowest (21,188.5). Intermediate values were observed for 26th (22,327.8) and 28th MW (21,975.3). These findings confirm that early sowing coincides with longer day lengths, ensuring greater photothermal accumulation, while delayed sowing reduces both day length and PTU availability. Ali *et al*. (2019) [23] similarly demonstrated that pearl millet sown early accumulated higher PTU and exhibited superior yield potential.

Phenophase-wise analysis showed that vegetative to flowering (P3) and grain filling to maturity (P6) accounted for the largest PTU requirements. For example, Phule Nachani accumulated 9,049.3 °C day hours during P3. This underscores the critical importance of photothermal resources for canopy expansion, photosynthesis, and reproductive initiation.

Hydrothermal Units (HyTU)

HyTU, reflecting the combined influence of thermal time and relative humidity, varied markedly across treatments (Table 4; Figure 4). Among varieties, Dapoli-3 again had the highest requirement (150,392.4 °C day hours), followed by Phule Nachani (147,371.0), while Phule Kasari required the least (129,919.3). These results suggest that Dapoli-3 depends more heavily on hydrothermal resources, while Phule Kasari efficiently completed its life cycle with fewer hydrothermal inputs.

Sowing windows showed notable differences, with the 28th MW (S3) recording the highest HyTU (142,887.1), closely followed by 24th MW (146,407.8). The lowest HyTU was observed under 30th MW (136,074.8). This pattern indicates that mid-season sowing aligns well with peak monsoon rainfall and moderate temperatures, enhancing hydrothermal balance.

Across phenophases, later stages, particularly heading to grain filling (P5) and grain filling to maturity (P6), demanded the highest HyTU. For instance, Dapoli-3 accumulated nearly 117,626 °C day hours during these stages. This confirms that moisture availability during grain filling is crucial for ensuring kernel weight and final yield.

Heat Use Efficiency (HUE)

Heat Use Efficiency (HUE), which expresses how effectively a crop converts accumulated heat units into biomass or grain yield, serves as a reliable indicator of varietal adaptability (Table 5; Figure 5). Among the varieties, Phule Kasari (V_2) exhibited the highest HUE for both grain yield (1.6 kg ha^{-1} °C day^{-1}) and biological yield (3.9 kg ha^{-1} °C day^{-1}). Phule Nachani (V_1) recorded intermediate values (1.3 and 3.1 kg ha^{-1} °C day^{-1}, respectively), while Dapoli-3 (V_3) had the lowest efficiency (1.2 and 2.8 kg ha^{-1} °C day^{-1}). These results highlight that conversion efficiency is more critical than total thermal accumulation. Despite recording the highest cumulative GDD, Dapoli-3 showed poorer efficiency in converting thermal energy into yield, likely due to higher maintenance respiration associated with its longer growth duration.

Sowing windows also exerted a significant influence on HUE. The 26th Meteorological Week (MW) (S_2) achieved the maximum grain HUE (1.5) and biomass HUE (3.4), closely followed by the 24th MW (1.4 and 3.3). The lowest efficiencies were recorded under 30th MW (1.3 and 3.1). These findings indicate that timely sowing allows the synchronization of critical reproductive stages with favorable temperature regimes, thereby enhancing the efficiency of heat utilization.

Crop phenology plays a crucial role in determining the appropriate timing of developmental processes. The duration of each phenophase governs the pattern of dry matter accumulation and partitioning among different plant organs. Dalton (1967) [6] emphasized that phenological observations can help specify the most suitable timing for specific developmental events. Similarly, Wang (1960) [20] reported that the duration of a particular growth stage is directly related to prevailing temperature, and that this duration for a given species can be predicted using the sum of daily mean air temperatures (i.e., heat units).

Light Use Efficiency (LUE)

The results of Light Use Efficiency (LUE) further supported the superior performance of Phule Kasari and timely sowing (Table 6; Figure 6). Among the varieties, Phule Kasari recorded the highest mean LUE (0.91 kg ha^{-1} MJ^{-1}), followed by Phule Nachani (0.88) and Dapoli-3 (0.82). The higher LUE of Phule Kasari can be attributed to its favorable physiological characteristics such as greater leaf area, efficient canopy structure, and enhanced radiation interception and utilization. Interception generally increased with the solar elevation angle, as at this latitude the sun reaches its zenith around 11:30 h, resulting in maximum insolation and higher PAR interception by the crop canopy (Chakraborty *et al*., 2008; Jena *et al*., 2009) [3, 10].

Across sowing windows, the highest LUE was observed under the 24th Meteorological Week (MW) (0.93 kg ha^{-1} MJ^{-1}), followed by the 26th MW (0.91 kg ha^{-1} MJ^{-1}). The lowest LUE (0.80 kg ha^{-1} MJ^{-1}) was recorded in the 30th MW. The reduction in LUE under delayed sowing can be explained by suboptimal light-temperature interactions during reproductive phases, leading to reduced canopy efficiency and biomass accumulation. These findings suggest that dry matter accumulation is significantly and positively influenced by intercepted PAR, particularly around 11:30 h when solar intensity is highest across phenophases. Similar relationships between solar radiation and dry matter production were reported by Ishikawa *et al*. (2003) [9] and Al-Khaffaf *et al*. (2003) [1], who observed strong positive correlations between radiation interception and biomass yield in cereal crops.

1. **Varietal performance:** Dapoli-3 consistently accumulated the highest GDD, HTU, PTU, and HyTU but demonstrated poor efficiency in HUE and LUE. In contrast, Phule Kasari, despite lower accumulations, translated available resources more effectively into biomass and grain yield. Phule Nachani showed intermediate performance.

2. **Sowing window effects:** Early sowing (24 MW) maximized GDD and PTU, while 30 MW maximized HTU but reduced efficiency indices. The 26 MW window consistently provided the best balance of thermal and hydrothermal resources with high efficiency, making it the most favorable sowing period.

3. **Physiological implications:** Efficiency indices (HUE and LUE) proved to be better indicators of yield than absolute accumulations. Phule Kasari's higher HUE and LUE reflect better partitioning, radiation interception, and tolerance to stress.

4. **Climate resilience:** Under projected climate variability, shorter-duration and more efficient varieties like Phule Kasari, combined with sowing in 26 MW, will likely ensure higher yield stability. These findings align with Shukla *et al*. (2021) [24] and Maitra *et al.* (2022) [25], who emphasized efficiency indices as key tools for climate-smart millet production.

Table 1: Phenophases wise Cumulative GDD (ºC day), HTU, PTU, HYTU required for various varieties of Finger millet crop during (*Kharif*, 2024)

Varieties (V)	Indices	P1	P2	P3	P4	P5	P6	Total
V_1- (Phule Nachani)	GDD	162.8	352.3	710.5	1043.8	1415	1879.4	1879.4
	HTU	388.9	793.2	1765.4	3239.2	5250.4	8426.8	8426.8
	PTU	2096.9	4525.6	9049.3	13162.8	17575.1	22855.8	22855.8
	HYTU	13139.4	28853.4	58988.3	85722.3	114348	147371	147371
V_2- (Phule kasari)	GDD	146.8	304.5	586.9	838.6	1078.7	1631.8	1631.8
	HTU	320.2	677.2	1364.8	2308.6	3424.5	6653.7	6653.7
	PTU	1890.9	3914.6	7502	10645.9	13585.1	20078.5	20078.5
	HYTU	11859	24905.3	48449.8	69025.1	88276.6	129919	129919
V_3-(Dapoli-3)	GDD	178.9	383.8	756.3	1090.4	1461.9	1932.8	1932.8
	HTU	418.2	886.2	1927	3470.7	5558.6	8771.3	8771.3
	PTU	2303.7	4927.3	9621.7	13723.1	18123.2	23338.9	23338.9
	HYTU	14504.8	31538.5	62695.9	89444.3	117626	150392	150392

Table 2: Phenophases wise Cumulative GDD (ºC day), HTU, PTU, HYTU required for various Sowing windows of Finger millet crop during (*Kharif*, 2024)

Sowing Windows (S)	Indices	P1	P2	P3	P4	P5	P6	Total
S_1-(24) MW	GDD	179.5	374	708.8	1015.4	1333.6	1832.1	1832.1
	HTU	809.5	1227.1	1583.3	2627.7	4051.8	6769.1	6769.1
	PTU	2333.1	4846.2	9154.1	13026.4	16951.4	22872.6	22872.6
	HYTU	13142.6	28533.1	56967.8	82397.1	107959	146408	146408
S_2-(26) MW	GDD	165.7	346.1	674.6	987.4	1304.6	1816.4	1816.4
	HTU	416.9	616.8	1256.4	2499.3	3979.9	7311.4	7311.4
	PTU	2137.1	4464.9	8640.3	12548.1	16402.3	22327.8	22327.8

	HYTU	13140.8	28473.7	56578.2	82104.4	107301	144874	144874
S_3-(28) MW	GDD	156.2	328.5	673.1	974	1303.6	1811.2	1811.2
	HTU	177.5	206.1	1550.8	2788.5	4691.7	8063.7	8063.7
	PTU	2014.6	4228.8	8571.9	12273.1	16185.2	21975.3	21975.3
	HYTU	13179	28560.7	56873.2	81165.6	106375	142887	142887
S_4-(30) MW	GDD	150	338.9	681.8	986.9	1332.2	1799	1799
	HTU	99.2	1092.2	2352.4	4109.3	6254.8	9658.3	9658.3
	PTU	1904	4283.3	8530.9	12194.6	16172.4	21188.5	21188.5
	HYTU	13208.5	28162.1	56426.1	79921.9	105366	136075	136075

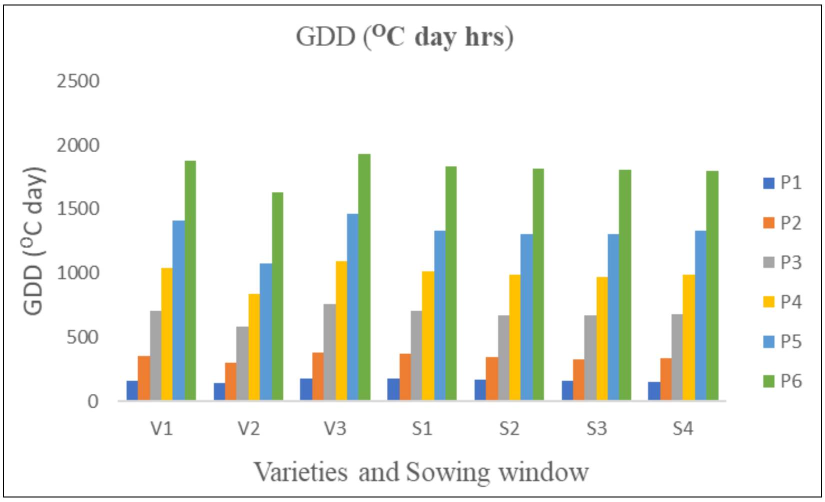


Fig 1: Growing degree days

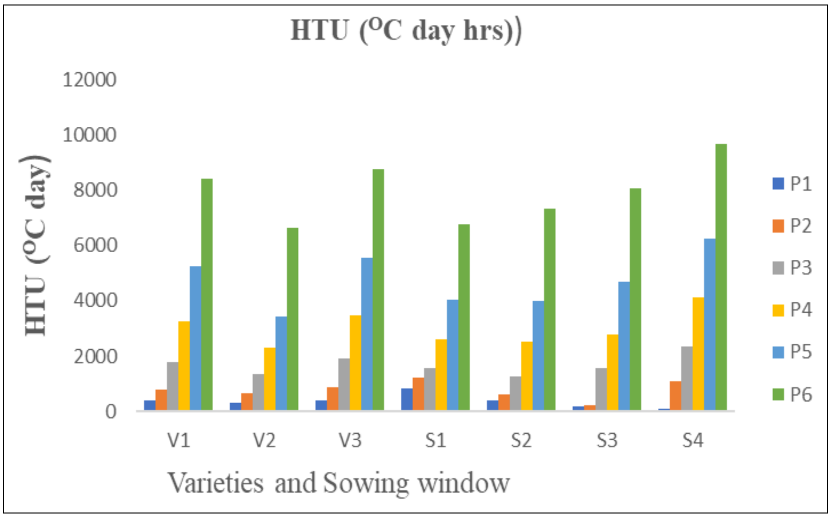


Fig 2: Helio thermal Unit

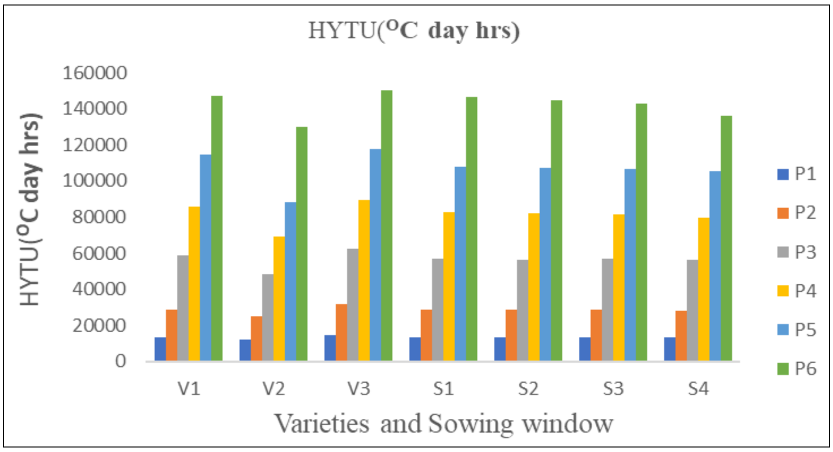


Fig 3: Hydrothermal unit

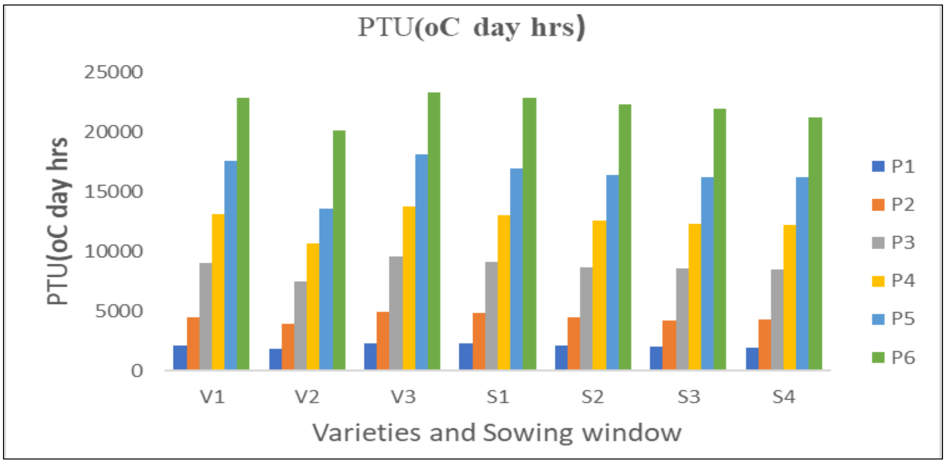


Fig 4: Photothermal unit

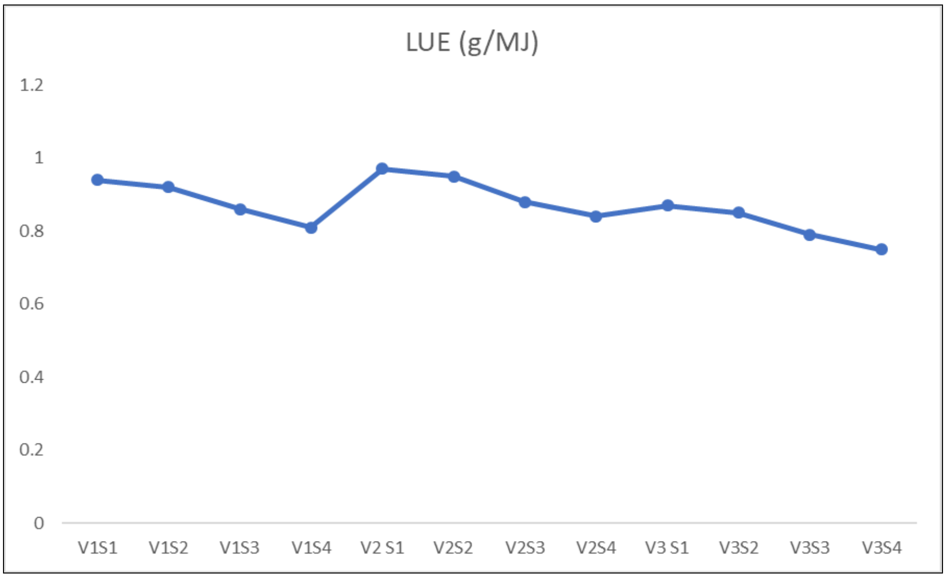
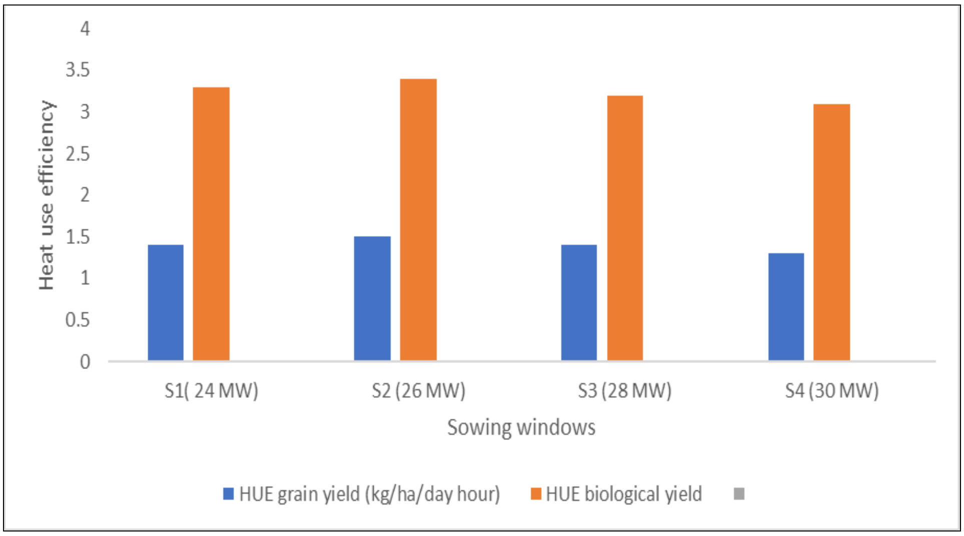


Fig 5: Light use efficiency of finger millet as influenced by different treatments



P1- Sowing to Germination P2- Germination to Vegetative P3- Vegetative to Flowering
P4- Flowering to Heading P5- Heading to Grain filling P6-Grain filling to Maturity

Fig 6: Heat use efficiency (kg/ha/day hr)

Table 3: Phenophases wise Cumulative HUE (Kg/ha/ °C day hour) and Light Use Efficiency required for various varieties and Sowing windows of Finger millet crop during (Kharif, 2024)

Treatments (Varieties and Sowing windows)	Grain yield (kg ha⁻¹)	Biological yield (kg ha⁻¹)	Accum. GDD (°C days)	HUE Grain yield (kg ha⁻¹ °C day⁻¹)	HUE Biol. yield (kg ha⁻¹ °C day⁻¹)	Mean final dry matter (g m⁻²)	Mean absorbed PAR (MJ m⁻²)	LUE Grain yield (kg ha⁻¹ MJ⁻¹)
V1 - Phule Nachani	2465.9	5862.5	1879.4	1.3	3.1	62.23	70.34	0.883
V2 - Phule Kasari	2635.7	6422.9	1631.8	1.6	3.9	65.56	72.08	0.91
V3 - Dapoli-3	2337.5	5427.7	1932.8	1.2	2.8	58.95	72.09	0.815
S1 - MW 24	2511.4	5976.6	1832.1	1.4	3.3	66.69	71.79	0.927
S2 - MW 26	2650.7	6257.2	1816.4	1.5	3.4	64.88	71.33	0.907
S3 - MW 28	2456.6	5850	1811.2	1.4	3.2	60.49	71.69	0.843
S4 - MW 30	2300	5533.3	1799	1.3	3.1	56.91	71.21	0.8

Weather-Yield Correlations

Grain yield showed strong positive correlations with rainfall ($r = 0.72$) and relative humidity ($r = 0.65$), and a negative correlation with maximum temperature ($r = -0.68$). These findings indicate that reproductive phases are particularly sensitive to moisture and temperature stress, aligning with earlier reports (Ray *et al*., 2021) [22].

Best Sowing Window and Variety

Sowing during 26 MW (late June) with Phule Kasari optimized thermal unit accumulation, efficiency indices, and yield. Early sowing (24 MW) also performed relatively well, while late sowing (30 MW) reduced HUE and yields due to terminal heat stress and shortened crop duration.

Conclusion

This study demonstrates that agro-meteorological indices including Growing Degree Days (GDD), Photo-Thermal Units (PTU), Helio-Thermal Units (HTU), Hydro-Thermal Units (HyTU), Heat Use Efficiency (HUE), and Light Use Efficiency (LUE) play a pivotal role in optimizing finger millet productivity under changing environmental and climatic conditions. The findings reveal that timely sowing during the 26th Meteorological Week and judicious variety selection (Phule Kasari) maximize the accumulation and utilization of thermal and hydrothermal resources, resulting in superior efficiency indices and grain yield. Positive correlations between yield, rainfall, and relative humidity, alongside negative associations with maximum temperature, underscore the crop's sensitivity to weather extremes, especially during the reproductive phase.

Agro-meteorological indices serve as powerful tools for quantifying crop-climate interactions, enabling precise sowing and varietal recommendations that promote resilience to climate variability. By improving resource-use efficiency (HUE, LUE), these metrics support both sustainable crop production and environmental stewardship in semi-arid and climate-vulnerable regions. Ultimately, strategic application of weather-based indices underpins climate-resilient millet cultivation, contributing to food security, improved livelihoods, and adaptation to future climatic uncertainties.

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